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WELDING RESEARCH

29, PARK CRESCENT, LONDON, W.1

ASSOCIATION NOTES

The Prospects of Welding High Strength Aluminium Alloys

Until recently it has been assumed that it is extremely unwise to attempt the fusion welding of the high strength aluminium alloys. Occasionally doubts have been expressed that we shall ever see welding applied to this desirable range of alloys. All too frequently such opinions have been a result of previous unfortunate experiences or of purely theoretical considerations. Now that we have the inert-gas shielded methods of welding, at least one of which is an established process, ought we not to take a more hopeful attitude and not just accept the situation as impossible? Providing more research is carried out and the results are used with care, the chances of applying welding successfully to the high strength alloys are good, but we can scarcely hope for a "magic wand" solution.

The most useful of all the aluminium alloys from the welding point of view are probably the binary alloys containing 3·5-5 per cent. magnesium. We can expect a greater tonnage of these alloys to be welded in the future than any other, particularly as the ship-building industry uses more aluminium alloys. At the moment, however, the magnesium-silicide H.10 alloy is probably equally popular for welding. This is a low strength heat treatable alloy in which, with present techniques, the maximum welded joint strength is about 12 tons per sq.in., a limit imposed by the strength of the heat-affected zone which gives a joint efficiency of about 60 per cent.—so presumably this is adequate for many applications.

Can similar static joint efficiencies be obtained with the higher strength heat treated alloys? Yes, but the welds in the high strength alloys are "brittle," whereas those in H.10 are "ductile"—at least that is the impression given by tensile tests in which the normal gauge lengths are used for measuring elongation. Elongation measurements on standard gauge lengths are worthless with welds, unless considered in conjunction with details of the mode of fracture, in particular precisely where the fracture occurred. It is regrettable that this vital information is so often lacking in accounts of work on weld strengths. In tensile tests, as-welded joints in H.10 mostly fail in the softened zone alongside the weld, where considerable elongation takes place. With the high strength alloys, however, fracture normally occurs in the weld, and because the heat-affected zone is considerably

stronger, most of the elongation takes place in the comparatively limited weld area. The low elongation figures are not necessarily a bad sign and it may be concluded that:—

1. There is a higher potential joint efficiency with the high strength alloys than with H.10, for although we can do little to reduce the heat-affected zone in H.10, we may be able to increase the strength of the weld metal in high strength alloy welds.
2. If weld metal could be developed with a strength equivalent to that of the heat-affected zone, elongation would occur in both weld and plate and good elongation figures should be obtained on the normal extended gauge lengths. Under such conditions we could expect a joint efficiency of up to about 80 per cent. in the as-welded condition in certain plate thicknesses.

Foundrymen may well regard the production of as-cast metal with a strength of 25 tons per sq.in. as impossible. Fortunately, however, weld metal is an extremely high grade casting which frequently exhibits properties intermediate between those of castings and wrought material. With the high rates of chilling in welding constituents may be retained in solution which make the weld metal responsive to ageing. This effect can further increase the strength of weld metal over that of an un-heat-treated casting.

The high strength alloys, of course, are susceptible to cracking—but so is the H.10 alloy. With tungsten-arc welding cracking is very much less than with gas-welding, and there is little evidence at the moment, that with this process the high strength alloys behave very differently from H.10. It is not intended to convey that there is no problem regarding cracking, but rather that we should not regard it as an insuperable difficulty.

Much important work on the cracking of a number of aluminium alloy systems has been carried out during the last decade by the Welding Research team at Birmingham University. Two papers by the former leader of this team, W. I. Pumphrey, which have a particular bearing on the problem of welding the high strength alloys, appear in the previous and present issues of *Welding Research*. These papers, dealing with the two alloy systems of particular interest, give some indication of the compositions likely to provide suitable filler alloys.

Research on the welding of high strength alloys can proceed in two principal directions:—

(*a*) Toward the development of a new high strength weldable alloy.

(*b*) The development of techniques for welding the existing alloys.

Work on the first of these alternatives has been carried out already, notably by Pendleton and Liddiard. A new weldable alloy is obviously the ideal solution, but its development is essentially a long-term project. Apart from the fact that there is an immediate need for welding the alloys already in existence, it should be appreciated that these alloys have been developed over many years to give the highest strength and best combination of other properties. It is unlikely, therefore, that another alloy with ideal welding characteristics could be produced without some sacrifice of strength or other useful property.

The key to welding the existing alloys must lie mainly in the selection of a suitable filler alloy. Research on this line is more straightforward and many of the factors which must be taken into consideration are known. Suitable filler alloys could give a reasonably good, if not ideal, solution to our problems, and in their development and use we might well gain knowledge which would enable an indirect approach to be made to the production of a new more easily weldable alloy. The B.W.R.A. are investigating the welding of high strength alloys for the Ministry of Supply and for the L.M.8 Committee, and are preparing a number of special filler alloys, a few of which may give the desired properties. A start has been made to the systematic investigation of three alloy systems.

The first step in the application of welding to the high strength alloys could probably be taken by users of heat-treated castings, followed by the substitution of welded plate structures for large forgings. In both these applications the welded product could be heat-treated to restore the properties of the plate and raise the strength of the weld metal. There must be a few applications in secondary structures where high strength alloy castings are being used that could be replaced with welded wrought material. If the components were fairly simple and not too thick, no matter how large, a reasonably satisfactory result might be achieved using the knowledge we have at present. In the production, testing and service of such components, we could gain much valuable experience and possibly also confidence.

It is often assumed that the designer must have 100 per cent. joint efficiency, but this is not always true, he is also concerned with such things as consistency and the ease with which the operation can be effected. There would doubtless be many applications where a joint efficiency as low as 60 per cent. would be acceptable if experience showed that such joints could be made easily and relied upon in service.

Now that the form of the welding processes has been established, the greatest advance in welding, as far as aluminium alloys are concerned, will be in the field of the high strength alloys. In applications where fatigue and stress corrosion are not the deciding factor, the prospects of applying welding to the high strength alloys are good.

P. T. HOULDCROFT.

METAL-ARC WELDING OF THICK ALUMINIUM - 5% MAGNESIUM PLATE

This report summarises work carried out by the Association on the causes of low weld strength in aluminium-magnesium alloy metal-arc welds. The preliminary work, which is briefly reviewed here, was published in the Dec. 1952 issue of "Welding Research." It is shown here, that by preventing sodium contamination of the weld metal, the weld efficiency can be raised from about 50 to 90 per cent. These results were obtained with electrodes produced in the laboratory and further work would be required to develop commercial electrodes capable of giving similar properties. The work was carried out on behalf of the Ministry of Supply to whom the Association would like to express its thanks for permission to publish the report.

By W. G. HULL, A.I.M., P. T. HOULDCROFT, B.Sc., J. D. CHADWICK, L.I.M.

SYNOPSIS

The investigations into the metal-arc welding of aluminium-5 per cent. magnesium plate began with an examination of welds produced with commercially available electrodes. All these welds had low strength, the poor results obtained being due to several factors, among them porosity and slag inclusions. In addition, it was thought that alkali metal contamination in the weld metal might be a cause of low weld strength.

It was found that weld metal porosity could be reduced by using plate and core wire of low gas content and by welding with electrodes coated by dipping in molten flux. The presence of intergranular porosity associated with columnar crystallisation was eliminated by the incorporation of grain refining elements in the core wire.

A new technique, called the "Twin Holder" or "Two Operator" technique was developed and resulted in fewer slag inclusions in the weld metal. It also doubled the overall speed of welding since delays due to slag removal at change-over points were not involved.

The effects on weld properties of traces of alkali metals introduced by constituents in electrode coatings during welding were investigated. It was shown that sodium in excess of 0·001 per cent. was deleterious, while lithium was not harmful up to the amounts encountered, i.e. 0·01 per cent. Sodium fluoride, present in the coating even in small percentages, readily introduced sodium into the weld, but negligible contamination occurred when sodium chloride only was present. Where other fluorides are included with sodium chloride, the possibility of the formation of sodium fluoride by double decomposition should not be excluded.

By controlling porosity, grain size, the presence of flux inclusions and sodium absorption in the weld metal, weld strengths were increased from 10·0 to 16·0 tons per sq.in., despite the fact that the electrode coatings generally had unsatisfactory running characteristics.

PRELIMINARY WORK[1]

The investigation was begun by an examination of butt-welded joints made in several thicknesses of plate using commercial electrodes. All the welds were found to have a low ultimate tensile strength, the strength of the welds in the thick plate being less than in the thin plate.

These preliminary tests were carried out on cold-rolled aluminium - 5 per cent. magnesium alloy plate of approximately ½ and 1 in. thicknesses. Analysis and mechanical properties of the plate material were as follows:

Plate Material Analysis

Mg	4·7 per cent.
Mn	0·29 ,,
Fe	0·25 ,,
Si	0·13 ,,
Na and Ca	Present
Gas content	0·50 ml./100 gm.

Mechanical Properties

	1 in. plate, as received	½ in. plate, as received
U.T.S. (tons per sq.in.)	21·2	22·0
Elongation (per cent.)	10 (on 8 in.)	11-16 (on 2 in.)

In the first welds prepared in the 1 in. thick plate, severe flux inclusions occurred. These were reduced considerably in later tests mainly by decreasing the number of passes as a result of slight weaving or the use of larger electrodes. All 1 in. thick plates were preheated to about 250 deg. C. before welding. Tensile tests were carried out on these welds with the reinforcing and penetration beads machined off. Typical results of these tests are given in Table I. The location of fracture in the tensile specimens in the 1 in. thick plate was usually in the weld metal, but in thin plate it was generally along the weld metal boundary. In the multi-run welds tested, fracture started in the root of the weld unless gross porosity or slag inclusions were present.

Table I

Plate Thickness (in.)	Type of Core Wire	U.T.S. (tons per sq.in.)
1	Al-5 per cent. Mg	11·0
1	Al-7 per cent. Mg	11·0
⅞	Al-5 per cent. Mg	8·0
⅞	Al-7 per cent. Mg	9·5

The strength of the metal-arc welds was below that obtained in gas welding (approximately 13·5 tons per sq.in. U.T.S.) and considerably lower than the strength of the parent material in the annealed condition, i.e. 18 tons per sq.in. U.T.S. Various factors which might have caused this generally low strength as well as the difference in strength between welds in thick and thin plate were then considered, among them the following:—

Porosity

This was of two types:—(*a*) pinhole, which was generally distributed, and in which the pores were rounded and of various sizes, and (*b*) intergranular, which was elongated and associated with columnar crystal growth; this type of porosity occurred mainly in multi-run welds (Fig. 1). Although the rounded porosity was obviously responsible for some loss of strength, it was thought that the elongated porosity was particularly harmful. Further tests with core wires containing titanium showed that the formation of columnar crystals could be avoided, thus preventing the occurrence of the elongated porosity (Fig. 2).

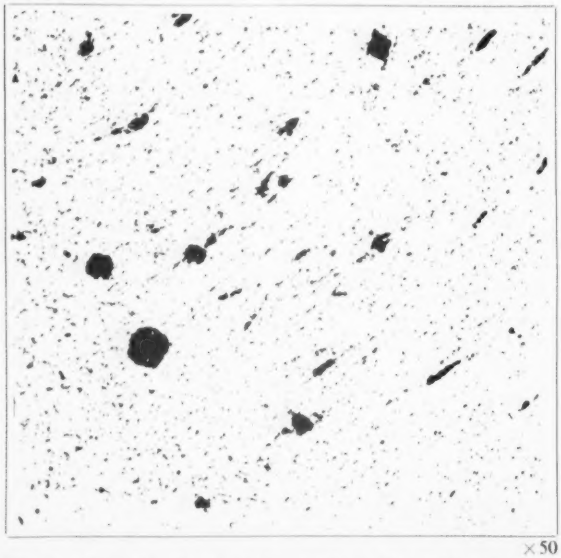

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Fig. 1. Example of elongated porosity in the weld metal of a multi-pass weld.

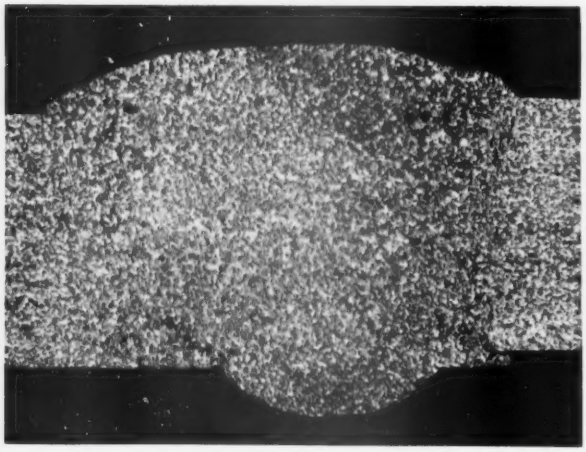

Fig. 2. Single-pass weld in half-inch plate using an electrode containing 0·5 per cent. titanium.

Magnesium Loss

It was found that there was a 20 to 30 per cent. loss of the magnesium of the core wire, and, since it was known that tensile strength increases with increasing magnesium content, it appeared desirable to use an aluminium-7 per cent. magnesium wire rather than an aluminium-5 per cent. magnesium wire to compensate for this loss. However, too high a percentage of magnesium was thought to be undesirable as it might increase the susceptibility to gas absorption. The results of the tests on the thin plate seemed to indicate that magnesium loss was not the predominant cause of low strength.

Minor Impurities

Analyses showed that the welds were contaminated with lithium and sodium, and since it was known that sodium in castings in this alloy was harmful, it was considered that these trace elements might be responsible for the generally low strength of metal-arc welds.

Weld Strengths in Thick and Thin Plate

The difference in tensile strength between welds in thick and thin plate led to a consideration of the effect of the number of runs deposited on the tensile strength of the joint. It was observed that there was a tendency for the fracture in tensile tests of multi-run welds to start at the root of the weld and it was thought that this might indicate that the runs deposited first had low strength.

In several multi-run welds fine cracks occurred in the first and second passes which were not readily observed except in micro-sections. These cracks were obviously a cause of low strength, but it was also thought possible that the heating of the first runs by the later weld beads might have an adverse effect on mechanical properties.

The preliminary work showed that metal-arc welds in the aluminium-5 per cent. magnesium alloy made with the electrodes which were then available could not be expected to give weld strengths of over 11 tons per sq.in. U.T.S. in thin material or over about 9 tons per sq.in. in plate of approximately 1 in. thickness.

Elongated porosity was shown to be a danger in certain circumstances and titanium additions to the filler wire to prevent columnar crystal structure in the weld metal were considered an advantage. Core wires containing up to 0·2 per cent. titanium were used in all subsequent work. It was also thought desirable that plate and core wires with a low gas content should be used in further work.

The presence in the weld metal of sodium and lithium was established and the possibility that these elements were responsible for the generally low strength of arc welds was considered.

CONTROL OF POROSITY*

Since in previous work gas porosity was a serious defect, and tended to mask the effect of other factors on the strength of the joint, it was decided to attempt the production of sound welds, even if the methods used had no application in practice.

This stage of the work was confined to single run welds in $\frac{1}{2}$ in. thick aluminium-5 per cent. magnesium specially degassed plate using $\frac{5}{16}$ in. diameter specially degassed aluminium-7 per cent. magnesium filler wire containing 0·2 per cent. titanium. Gas content of the wire was 0·50 per ml. 100 gm.

The plate was rolled from chlorine degassed, semi-continuous cast slabs, and supplied in the hot-rolled, annealed and flattened condition. The plate analysis and mechanical properties were as follows:—

* B.W.R.A. Committee Report L.M.1/14.

Plate Material Analysis

Mg	5·09 per cent.
Mn	0·24 „
Fe	0·16 „
Si	0·12 „
Cu	0·048 „
Ti	0·03 „
Gas content	0·25 ml. per 100 gm.

Mechanical Properties

U.T.S. tons per sq.in.	18·5
Elongation (2 in.)	30 per cent.

Most of the tests were made with rods dipped in molten flux of the composition quoted as Flux "A." The remainder were made with commercially coated slurry dipped rods dried at 250 deg. C. and 500 deg. C.

Composition of Flux "A"

Sodium chloride	23·5 per cent.
Potassium chloride	28·3 „
Sodium fluoride	5·5 „
Potassium fluoride	7·2 „
Aluminium fluoride	6·5 „
Lithium chloride	9·2 „
Cryolite	19·8 „

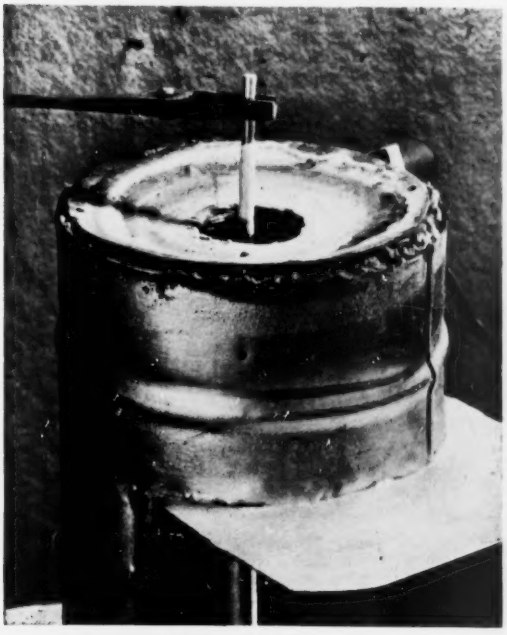

Fig. 3. Applying an electrode coating by hot-dipping.

The electrodes were dipped in molten flux contained in an "Inconel" pot 12 in. deep, heated in a vertical tube furnace (see Fig. 3). The flux was heated for several hours at 750 deg. C. in order to eliminate water-of-crystallisation and cooled to 570 deg. C. just prior to dipping. The rods were pickled in a 2 to 5 per cent. aqueous solution of sodium fluoride and sulphuric acid and then heated in an air furnace to 250 deg. C., dipped and returned to the furnace until required—being scarcely cool when welding began.

The edge preparation was a 70 deg. included angle Vee with a small Vee at the reverse side, the plates being closely butted. Plate edges and electrode rods were carefully cleaned by scratch brushing and pickling. The plates were pre-heated to drive off surface moisture and a steel grooved back-up bar was used.

Since metal-arc welding is an intermittent process, a technique was evolved to increase the over-all speed of the operation by minimising the delays due to changing electrodes and chipping the slag at the change-over point. Two electrode holders, each with about 5 ft. of lead were connected to the main lead from the generator. Both holders were loaded, and when the first electrode had been nearly used, the second holder was passed to the welder who quickly changed hands and continued welding with the new electrode. While this electrode was being used, the first holder was reloaded. An alternative and better procedure was the use of two operators welding alternately. The second operator would warm the end of his electrode near the arc and when the first electrode was almost used, he would move his own electrode closer so that the arc transferred to the new rod and welding continued without a break.

Using the "Twin-holder" technique the overall welding speed was increased from 2½ in. per minute to 5 in. per minute by eliminating the need to chip away the slag at the end of each run. The quality of welds was also improved since slag inclusions and inadequate penetration at the electrode change points were eliminated. The use of this technique is illustrated in Fig. 4, and a section of a weld in 1 in. thick plate is given in Fig. 5.

Typical results obtained in these tests to reduce porosity are given in Table II.

Table II.—Mechanical Properties of Metal-Arc Welds in ½ in. Aluminium-5 per cent. Magnesium Plate, using $\frac{5}{16}$ in. Diameter Aluminium-7 per cent. Magnesium Core Wire

Type of Coating	Electrode Drying (temp. deg. C.)	Plate Preheat (temp. deg. C.)	Average U.T.S. (tons per sq.in.)	Weld Porosity
Commercial, slurry dipped	250	250	6·9	Very severe
	500	225	9·5	Considerably reduced
Hot dipped using Flux "A"	—	250	10·5	Moderate

Fig. 4. Two-operator/twin-holder technique, at changeover point.

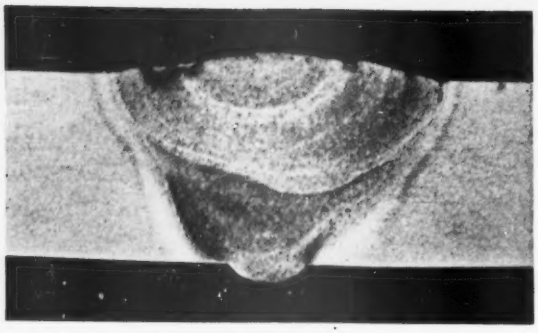

Fig. 5. 1 in. thick butt weld in aluminium-5 per cent. magnesium plate. Two passes, using the twin holder technique.

Examination of the fractures showed that failure occurred in the weld metal at the edge of the weld; this mode of fracture appeared to be typical for metal-arc welds in this material. Tests carried out on material cut from the weld metal showed that it was not appreciably stronger than the complete joint, and it was considered, therefore, that this fusion zone failure in testing was not in itself significant.

It will be seen from Table II that the measures taken to reduce porosity have resulted in weld strengths being raised from 6·9 tons per sq.in. to 10·5 tons per sq.in., but even this higher strength was much below the strength of 17·0 tons per sq.in. obtained on argon-arc welds in this material. These results showed that the advantage of hot dipping over drying at 500 deg. C. was not very great. Although porosity had not been eliminated, it was reduced to a point where it could not have been responsible for a serious reduction in strength. Clearly, the low strength of metal-arc welds in the aluminium-magnesium alloys was due to some factor not previously investigated.

THE EFFECT OF THE ALKALI METALS * † ‡

It has generally been recognised that the presence of sodium as an impurity has a harmful influence on the mechanical properties of cast aluminium alloys containing a high percentage of magnesium, in particular the aluminium-10 per cent. magnesium alloy. There appears to be little published work concerning the mechanism by which sodium lowers the mechanical properties of this type of alloy. Mondolfo[2] refers briefly to the embrittling effect of sodium on aluminium alloys containing magnesium and considers the possibility of the formation of an intermetallic compound between sodium and magnesium which precipitates at the grain boundaries. Similarly, it was thought that lithium in the weld metal may be undesirable since Pendleton[3] had reported that aluminium-7 per cent. magnesium alloy ingots containing small amounts of lithium (up to 0·1 per cent.) were susceptible to cracking during hot rolling.

As it was known that lithium and sodium were absorbed by the weld metal, it was decided to investigate their effects on the mechanical properties of welds in the aluminium-5 per cent. magnesium alloy. This was done by making a series of metal-arc welds using a flux normally used in the casting of this alloy containing neither lithium nor sodium. A second set of welds was made using a flux containing a lithium salt and a third set containing a sodium salt. The results obtained were compared with one another and with those obtained earlier, using Flux "A," which contains both lithium and sodium salts. As the effect of these elements individually on weld strengths was found to differ considerably, further tests were made involving argon-arc welds which had intentionally been contaminated with lithium or sodium.

* B.W.R.A. Committee Report L.M.1/19.
† B.W.R.A. Committee Report L.M.1/23.
‡ B.W.R.A. Committee Report L.M.1/27.

The Effect of Lithium

The effect of lithium in the weld metal was investigated by making two sets of metal-arc welds, each in $\frac{1}{4}$ in. and $\frac{1}{2}$ in. thick plate using $\frac{3}{16}$ in. and $\frac{5}{16}$ in. diameter aluminium-7 per cent. magnesium wire respectively. One set of welds was made with a flux that contained neither lithium nor sodium, and the other with sodium-free, lithium-containing flux:—

Composition of Flux "B"

		Per cent.
No lithium, no sodium.	Anhyd. magnesium chloride	55
	Magnesium fluoride ..	10
	Potassium chloride ..	35

In preparing the lithium-containing flux, it was originally intended to replace the potassium chloride of Flux "B" with lithium fluoride so that the proportions of magnesium chloride and magnesium fluoride would remain unchanged. It was found, however, that the flux was incompletely molten at 600 deg. C., and was too hygroscopic. After some small scale experiments to produce a flux of the right fluidity and melting point, the following flux was employed:—

Composition of Flux "C"

		Per cent.
Lithium, but no sodium.	Anhyd. magnesium chloride	55
	Lithium fluoride	5
	Potassium chloride ..	40

In all cases, the electrodes were coated by hot dipping in molten flux using the technique previously described. Both types of electrode coatings were found to possess certain unfavourable welding characteristics, but, as the prime object in their use was to determine the effect of lithium on the weld strength the welding characteristics of the fluxes were not taken into consideration. The mechanical properties obtained from the welds are given in Table III.

Table III.—Mechanical Properties of Metal-Arc Welds made in Aluminium-5 per cent. Magnesium Plate using Aluminium-7 per cent. Magnesium Filler Wire. Flux Compositions are given above.

Plate Thickness (in.)	Flux Used	Min. U.T.S. (tons per sq.in.)	Max. U.T.S. (tons per sq.in.)	Average U.T.S. (tons per sq.in.)
$\frac{1}{4}$	Flux "B"	13·4	16·2	15·1 (12)*
$\frac{1}{4}$	Flux "C"	14·8	16·9	15·8 (15)
$\frac{1}{2}$	Flux "B"	10·7	14·4	13·0 (11)
$\frac{1}{2}$	Flux "C"	9·2	14·8	12·3 (20)

* Figures in parentheses show the number of tests used to obtain the averages shown.

It will be seen that the results obtained using the lithium-bearing flux "C" showed little difference from those obtained using flux "B," which is lithium-free. Since spectrographic analysis showed that the weld metal had absorbed 0·01 per cent. lithium (see Table VII), it appeared that lithium had no deleterious effect on the weld properties up to the concentrations encountered.

Argon-Arc Welds Contaminated with Lithium

The effect of lithium was then investigated further by making a number of argon-arc welds using aluminium-5 per cent. magnesium wire and plate from the same batch as that used for the other tests.

After the wire and plate had been cleaned, the plate edges were coated with a thin layer of an alcoholic paste containing lithium fluoride in suspension. This layer was then dried out by gently heating with a gas flame. The presence of the salt made welding somewhat difficult and weld appearance was poor, but radiographic examination showed that the weld metal was free from salt inclusions. Table IV gives the results of mechanical properties obtained.

Table IV.—Effect of Lithium and Sodium on the Strengths of Argon-Arc Welds in $\frac{1}{4}$ in. thick Aluminium-5 per cent. Magnesium Plate using $\frac{1}{16}$ in. Diameter Filler Rod of the Same Composition.*

Type of Weld	Percentage Li in Weld	Percentage Na in Weld	Average U.T.S. (tons per sq.in.)
Normal argon-arc weld ..	Nil	Nil	17·0
Plate edge coated with lithium fluoride	0·01	Nil	17·0
Plate edge coated with sodium fluoride	Nil	0·055	10·9

* As there is virtually no magnesium loss from the filler wire in argon-arc welding, aluminium-5 per cent. magnesium filler wire was used instead of the aluminium-7 per cent. magnesium wire normally used in metal-arc welding.

It will be seen that the argon-arc welds made with the addition of lithium fluoride gave results similar to those shown by normal argon-arc welds in this material, although the weld metal contained 0·01 per cent. of lithium.

The Effect of Sodium

Using the same materials and technique as described in previous sections, the effect of sodium was investigated by making two sets of welds using the sodium-free Flux "B" and a flux containing a sodium salt of the following composition:

Composition of Flux "D"

		Per cent.
Sodium, but no lithium.	Anhydrous magnesium chloride	.. 55
	Magnesium fluoride	.. 10
	Sodium chloride ..	.. 35

As before, the electrodes were coated by hot dipping in the molten flux. The coatings were found to have certain unfavourable welding characteristics, but were not taken into consideration in making these tests. The weld strengths obtained are shown in Table V:

Table V.—Mechanical properties of metal-arc welds in Aluminium-5 per cent. Magnesium plate, using Aluminium-7 per Cent. Magnesium wire coated with fluxes "B" and "D".

Plate Thickness (in.)	Flux Used	Min. U.T.S. (tons per sq.in.)	Max. U.T.S. (tons per sq.in.)	Average U.T.S. (tons per sq.in.)
$\frac{1}{4}$	Flux "B"	13·4	16·2	15·1 (12)*
$\frac{1}{4}$	Flux "D"	13·5	16·0	14·5 (7)
$\frac{1}{2}$	Flux "B"	10·7	14·4	13·0 (11)
$\frac{1}{2}$	Flux "D"	11·0	13·0	11·9 (5)

* Figures in parentheses indicate the number of tests used to obtain the average U.T.S. figure.

It will be seen that these results are higher than those previously obtained using the conventional types of flux coatings, but that the difference in strengths between the welds made with the sodium-free and the sodium-bearing fluxes was not appreciable. It was found later, however, that the degree of sodium absorption from Flux "D" was much less than encountered in the earlier work where fluxes containing sodium fluoride were involved. This led to an investigation of the effect of sodium fluoride on argon-arc welds.

The technique used was the same as that described in the previous section. Welding was difficult, and weld appearance poor, but radiographic examination showed that no inclusions of the salt were present in the weld metal. It will be seen from Table IV that the presence of sodium fluoride caused a very severe drop in the tensile strength of the welds, and that the weld metal contained 0·055 per cent. sodium.

Table VI summarises the mechanical test results obtained with each of the different fluxes used in this investigation, relating these properties to the sodium and lithium content of the fluxes.

Table VI.—Summary of Mechanical Properties of Metal-Arc Welds made in Aluminium-5 per cent. Magnesium Plate using Aluminium-7 per cent. Magnesium Core Wire Coated with Fluxes A, B, C and D.

Flux	Sodium Compound Present (per cent.)	Lithium Compound Present (per cent.)	Average U.T.S. $\frac{1}{4}$ in. Plate (tons per sq.in.)	Average U.T.S. $\frac{1}{2}$ in Plate (tons per sq.in.)
Flux "A"	As chloride, 23·5. As fluoride, 5·5. As fluoride, in cryolite, 12·0	As chloride, 9·2	11·0	10·0
Flux "B"	Nil	Nil	15·1	13·0
Flux "C"	Nil	As fluoride, 5	15·8	12·3
Flux "D"	As chloride, 35	Nil	14·5	11·9

CHEMICAL AND SPECTROGRAPHIC ANALYSIS

It was thought that the improved strengths obtained on some of the welds made with fluxes of the magnesium salts type might be due to the deposit containing substantially higher magnesium than that present in welds where a more conventional type of coating had been employed. Magnesium determinations were therefore carried out on the weld metal from metal-arc welds made with each of the fluxes described. In all cases the magnesium content varied from 5·17 to 5·44 per cent., and although the welds involved showed wide differences in mechanical properties, it was considered that the difference in the magnesium content found was not sufficient to account for this variation.

Spectrographic analyses were carried out to determine the alkali metal content of the parent plate and the weld metal from the various metal-arc and argon-arc welds involved in the investigation. The results are given in Table VII on the next page.

CONSIDERATION OF RESULTS

Consideration of the mechanical properties and the magnesium contents of the metal-arc welds tested, indicate that the slight differences in the magnesium content of the weld metal were not sufficient to account for the wide variations in the mechanical properties obtained.

The presence of traces of sodium and lithium in the weld metal deposits is probably due to the reaction of the halides at the metal surface with aluminium and magnesium. It is also probable that the fluorides react more readily than the chlorides, which will explain the increased sodium contamination when the flux contains sodium fluoride. Thus, in Table VII, 0·010 per cent. sodium was found in the weld

Table VII.—Results of Spectrographic Analyses of Metal-Arc and Argon-Arc Welds in ½ in. thick Aluminium-5 per cent. Magnesium Plate. The Parent Plate showed no Trace of Sodium, Lithium, Potassium or Calcium.

Type of Weld	Flux	Flux Compositions (per cent.)	U.T.S. (tons per sq.in.)	Results (per cent.)
Metal-arc	Flux "A"	(See text)	10·6	Na, 0·01 Li, 0·015 No trace of K or Ca
Metal-arc	Flux "B"	$MgCl_2$, 55 MgF_2, 10 KCl, 35	14·4	No trace of Na, Li, K or Ca
Metal-arc	Flux "C"	$MgCl_2$, 55 LiF, 5 KCl, 40	14·2	Li, 0·01 No trace of Na, K or Ca
Metal-arc	Flux "D"	$MgCl_2$, 55 MgF_2, 10 NaCl, 35	13·6	Na, 0·001 No trace of Li, K or Ca
Argon-arc	Coated with lithium fluoride		17·0	Li, 0·01 No trace of Na, K or Ca
Argon-arc	Coated with sodium fluoride		10·9	Na, 0·055 No trace of Li, K or Ca

deposit when the coating contained 23·5 per cent. sodium chloride, 19·8 per cent. cryolite and 5·5 per cent. sodium fluoride, but only 0·001 per cent. sodium was found when the coating contained as much as 35 per cent. sodium chloride, but no sodium fluoride or cryolite.

It would appear from these results that where a flux contains sodium fluoride, a considerable degree of sodium absorption in the weld metal can be expected, and that sodium contamination of approximately 0·01 per cent. or more is deleterious to mechanical properties. Where a flux coating contains sodium chloride and not sodium fluoride, the sodium content of the weld metal may be sufficiently low to have no serious effect on the strength of the weld. Lithium, however, does not appear to be harmful to weld strengths in the amounts (0·01 per cent.) so far encountered. From Table VII it would appear that no absorption of potassium takes place.

CONCLUSIONS

1. Porosity.—Because of its high magnesium content, this material is particularly susceptible to gas porosity, but this can be minimised by taking the following precautions:—

(i) Using plate and filler wire of low gas content.

(ii) Using a grain refining element (e.g. titanium) in the filler wire to eliminate columnar crystal growth and the elongated porosity associated with it.

(iii) Storing the electrodes in a dry, warm place, drying them at a high temperature just prior to welding, or using the hot dipping procedure for coating.

(iv) Excluding hygroscopic salts from the electrode coating.

2. Magnesium Loss.—There is a loss of 20 to 30 per cent. of the magnesium of the core wire which may be offset by using a core wire containing a higher percentage of magnesium.

3. Alkali Metals.—Sodium contents of 0·01 per cent. in the weld metal are seriously detrimental to weld properties while 0·001 per cent. sodium in the weld metal reduces weld strengths only slightly. It appears that harmful absorption of sodium by the weld metal may occur when the flux contains sodium fluoride. Where a flux contains sodium chloride only, the degree of sodium absorption is very small, and it would seem that a small percentage of sodium chloride may be permitted, but sodium fluoride or any mineral containing it should, however, be excluded. The possibility of double decomposition between the chloride and fluoride should not be overlooked.

Concentrations of up to 0·01 per cent. lithium in the weld metal are not injurious to weld strengths. No potassium contamination of the weld metal has been observed.

ACKNOWLEDGMENTS

Acknowledgments are gratefully made for the generous assistance given in these investigations by the British Aluminium Co. Ltd., The Fulmer Research Institute and the British Non-Ferrous Metals Research Association, who carried out the analyses.

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SOME ALUMINIUM-COPPER-SILICON ALLOYS

AN EXAMINATION OF THEIR TENSILE PROPERTIES AND OXY-ACETYLENE WELDING CHARACTERISTICS

An examination has been made of the tensile properties and oxy-acetylene welding characteristics of a number of aluminium-copper-silicon alloys. The alloys examined were susceptible to heat-treatment and show promise as medium strength alloys with good welding properties in either the heat treated or annealed condition. The Association is indebted to The Aluminium Development Association for permission to publish this work.

By W. I. PUMPHREY,* M.Sc., Ph.D.

INTRODUCTION

Although there are several references in the literature to the tendency of individual alloys in the aluminium-copper-silicon system to crack during casting and welding, no systematic work on the welding and tensile properties of alloys in this system appears to have been done. Pendleton and Liddiard,[1] however, have made an investigation of such properties in a limited number of aluminium-copper-silicon alloys of commercial purity.

In an earlier investigation by Jennings, Singer and Pumphrey,[2] an examination was made, by means of restrained weld tests, of the tendency of aluminium-copper-silicon alloys of high purity containing 0 to 10 per cent. copper and 0 to 4 per cent. silicon to crack during welding. The results of this examination are reproduced in Fig. 1, in which the tendency to cracking of the different alloys is indicated by means of contour lines of equal cracking intensity. From these results, the six alloys listed in Table I having the most promising properties as regards freedom from cracking during welding were selected for further welding and mechanical tests, and the results obtained in these tests are recorded and discussed in the present paper.

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EXPERIMENTAL WORK

The alloys chosen for examination were made from high purity materials and the actual chemical compositions of the alloys were almost identical with the nominal compositions—the amount of impurity present in all the alloys being low, consistent with their having been prepared from pure materials; the complete analyses of the alloys have therefore not been recorded in Table I. The welding and tensile properties of the six alloys in the annealed and heat-treated conditions were determined. The annealing treatment consisted in maintaining the alloys at 360 deg. C. for one hour, followed by slow cooling from that temperature, and the heat-treatment comprised solution treating at 515 deg. C. for five hours, followed by ageing for twelve hours at 160 deg. C. to 165 deg. C., the test sheets being flattened before ageing.

Restrained weld tests, using oxy-acetylene welding and filler rods of the same composition as the sheets being welded, were carried out on all the alloys chosen for investigation and an examination was made of the tensile properties of the alloys before welding and of the tensile properties of welds made in annealed and heat-treated material.

The welding and mechanical tests were made on material rolled down to sheets 0·080 in. in thickness, the tensile test pieces from the unwelded material being machined to conform to B.S.485 with the centre parallel portion of each specimen transverse to the direction of rolling of the sheet.

Table I.—Mechanical Properties of Aluminium-Copper-Silicon Alloys

Nominal Composition		Results of Tests on Annealed Material				Results of Tests on Heat-treated Material			
Cu (per cent.)	Si (per cent.)	U.T.S. (tons per sq.in.)	0·1 per cent. Proof Stress (tons per sq.in.)	Elongation* (per cent.)	Hardness (D.P.H.)	U.T.S. (tons per sq.in.)	0·1 per cent. Proof Stress (tons per sq.in.)	Elongation* (per cent.)	Hardness (D.P.H.)
0	4	6·7	2·1	24·5	30	9·5	4·5	20·0	53
8	0	8·85	2·5	18·5	39·5	25·6	14·4	12·0	122·5
2	3	10·0	2·4	22·5	41	14·5	6·25	16·0	75
2	4	9·2	2·6	22·5	40	15·0	7·55	16·0	75
4	1·5	9·2	2·65	26·5	39	24·5	14·5	9·5	124·5
6	2	10·4	2·8	24·0	43·5	26·1	16·5	13·0	128

* Percentage elongation on 2 in.

For the tensile tests of the alloys after welding, test pieces were machined from those welded sheets in which weld cracking was not too severe to make testing impossible, the weld being located at the mid-point of the centre parallel portion of the test piece and transverse to the length. The excess weld metal in the reinforcement and underbead was machined away before tensile testing to give specimens of uniform thickness along their length.

EXPERIMENTAL RESULTS

(i) Tensile Properties of the Alloys

The results of hardness and tensile tests on the alloys in the heat-treated and annealed conditions are summarised in Table I, and the results of tensile tests of the welds made in the six alloys in these two conditions are given in Table II.

The results in Table I indicate that the alloys containing a preponderance of copper were very susceptible to heat-treatment and had good mechanical properties in the heat-treated condition. The strengths of the heat-treated alloys were, however, considerably reduced by welding, the strengths of certain of the alloys after welding being less than half those before welding.

Where fracture occurred in the basis metal in the tests of the welded specimens, the properties of the weld metal could not be determined but obviously the strength of the weld was greater than that of the basis metal. When fracture occurred in the basis metal in the tensile tests of the material welded in the annealed condition, the ultimate tensile strength of the welded material was similar to that of the annealed material before welding, but the elongation was considerably lower. This latter anomaly was also noticed by Pendleton and Liddiard, and may possibly be ascribed to the relatively high proof stress of the cast material in the weld, which, in the initial stages of testing, does not yield in tension and has the effect of reducing the general elongation and concentrating the stress on those parts of the basis metal which are the first to yield. The elongations of the alloys welded in the heat-treated condition were somewhat less than those of the same alloys welded in the annealed condition, possibly because of an inversion of the above effect—that is, because the higher proof stress of the basis metal concentrates the stress, and causes fracture to occur, in the relatively non-ductile cast material of the weld.

The compositions of the alloys examined in the present investigations were, in general, outside the range of compositions examined by Pendleton and Liddiard. In the few instances where the results can be compared, however, they are in reasonable agreement, particularly in view of the fact that the alloys examined by Pendleton and Liddiard were of commercial purity.

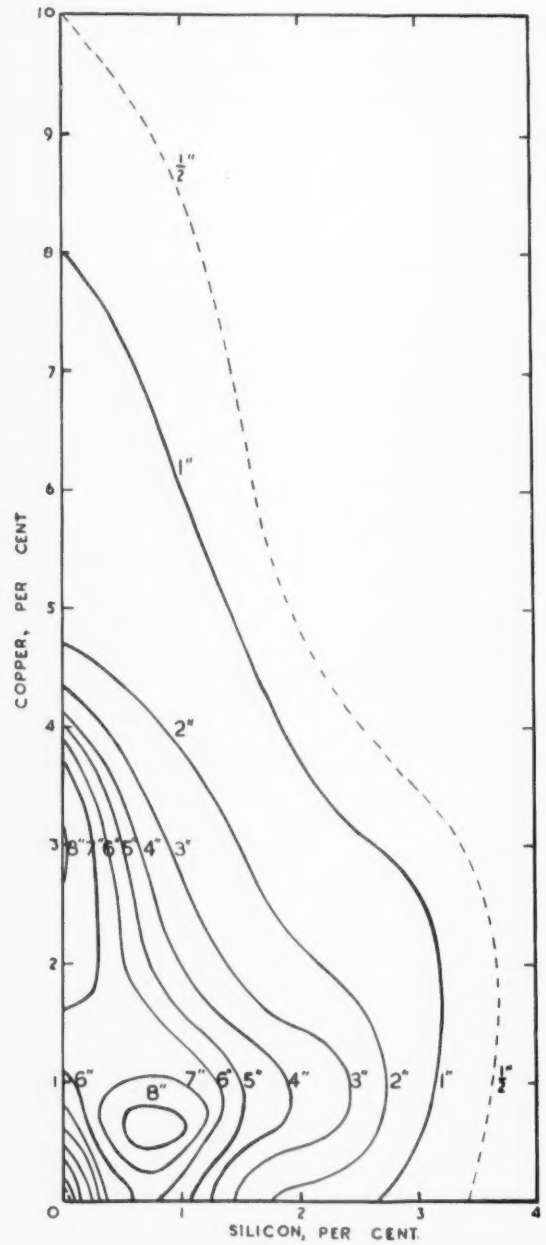

Fig. 1. Ternary diagram of cracking of restrained welds in aluminium-copper-silicon-alloys.[2]

(ii) Welding Properties of the Alloys

With all the alloys the tendency to crack in the restrained weld test was low, and there was little difference in this tendency whether the alloys were welded in the annealed or heat-treated condition. The appearance of the weld in an aluminium-copper-silicon alloy welded in the annealed condition is shown in Fig. 2; in this instance the length of weld cracking in the restrained weld test was 1·2 in.

The alloys welded readily and there was no tendency for the welds to fall through or for blistering or porosity to occur in the vicinity of the weld. There was, however, some slight tendency for the underbead to fissure at the finishing end of the weld in the alloy containing 4 per cent. copper and 1·5 per cent. silicon, as illustrated in Fig. 3. Fissuring was not observed in any other alloy, and the slight occurrence of this defect in the alloy containing 4 per cent. copper and 1·5 per cent. silicon would be unlikely to lead to any serious cracking under industrial conditions of welding.

DISCUSSION AND CONCLUSIONS

The results in Table II show that, provided the weld is sound, fracture in tensile test specimens of aluminium-copper-silicon alloys welded in the annealed condition occurs, in general, in the basis metal, indicating a higher strength in the cast, than in the annealed condition. The alloy containing 2 per cent. copper and 3 per cent. silicon is, however, an exception. The strength of the alloy containing 4 per cent. silicon is also greater in the cast than in the heat-treated condition.

All the aluminium-copper-silicon alloys examined had good mechanical properties in the heat-treated condition, although, as might be expected, the alloys containing more

Table II.—Mechanical Properties of Oxy-Acetylene Welds in Aluminium-Copper-Silicon Alloys

Nominal Composition		Results of Tests on Welds made in Annealed Material				Results of Tests on Welds made in Heat-treated Material			
Cu (per cent.)	Si (per cent.)	Average Length of Cracking in Restrained Weld Test (in.)	U.T.S. (tons per sq.in.)	Elongation* (per cent.)	Position of Fracture	Average Length of Cracking in Restrained Weld Test (in.)	U.T.S. (tons per sq.in.)	Elongation* (per cent.)	Position of Fracture
0	4	0·2	6·6	18·5	In basis metal†	0·3	8·0	14·0	In basis metal
8	0	1·0	10·1	10·5	In basis metal	1·1	13·25	5·0	In weld
2	3	1·2	10·1	9·0	In weld	1·0	10·8	10·0	In weld
2	4	0·05	10·9	13·0	In basis metal	0·1	11·4	8·0	In weld or weld area
4	1·5	1·4	10·3	11·5	In basis metal	1·4	12·25	6·5	In weld
6	2	0·05	10·1	6·0	In basis metal	0·2	10·9	3·0	In weld or at edge of weld

* Percentage elongation on 2 in.

† In basis metal indicates that fracture occurred at a point remote from the heat-affected zone of the weld.

silicon than copper were less susceptible to heat-treatment than the alloys of higher copper content. The process of welding caused a marked reduction in the properties of the heat-treated alloys, but welds in these were appreciably stronger than in the annealed alloys. The ductility of the welds in the heat-treated alloys was lower than that of the heat-treated alloys before welding, and of the welds in the annealed alloys.

None of the aluminium-copper-silicon alloys welded in the heat-treated condition fractured in the heat-affected zone of the weld during tensile testing. This result would seem to support the observation of Pendleton and Liddiard that in aluminium-copper-silicon alloys of varying silicon contents there is little or no harmful heat-affected zone after welding if the alloys contain no magnesium.

The aluminium-copper-silicon alloys free from magnesium thus show promise as medium strength alloys with good welding properties. For applications where reasonably high strength in the heat-treated condition and moderate welding properties are required, material based on the alloy containing 4 per cent. copper and 1·5 per cent. silicon is indicated; for good welding properties first but moderate strength also, the alloy containing 2 per cent. copper and 4 per cent. silicon, or a composition between this and the previous alloy, should be of value.

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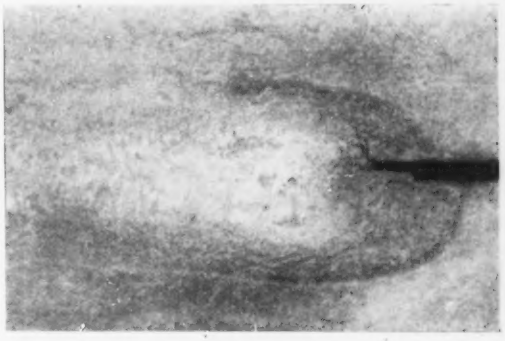

Fig. 2. Appearance of oxy-acetylene weld in aluminium-copper-silicon alloy containing 2 per cent. copper and 3 per cent. silicon welded in annealed condition. Length of weld cracking, 1·2 in. Unetched × 1.

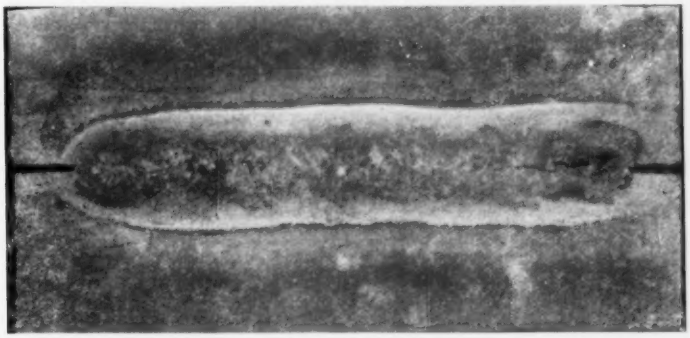

Fig. 3. Fissuring of underbead at finishing end of oxy-acetylene weld in aluminium-copper-silicon alloy containing 4 per cent. copper and 1·5 per cent. silicon welded in annealed condition. Unetched × 2·5.

GASEOUS ADDITIONS TO THE ARGON SHIELD IN WELDING ALUMINIUM

This paper by Dr. D. C. Moore was the joint prize winning paper for the 1950 British Oxygen Company's prize for original research into welding or its application. The opinions expressed are those of the author and not necessarily those held by B.W.R.A.

By D. C. Moore, B.Met., M.Sc., Ph.D. *

INTRODUCTION

When the argon-arc welding process was first introduced into Great Britain in 1943 for welding the magnesium-rich alloys, the highest purity argon available was only of the order of 98·5 per cent. and often much less. However, argon of this purity was found to be reasonably satisfactory for the welding of magnesium and its alloys. Since 1943 the process has been applied successfully to many other materials, including stainless steel, and finally to aluminium and its alloys. With the increased demand for argon, the manufacturers raised the purity to nominally 99·5 per cent., but such gas was not found to give consistently satisfactory welds in aluminium-base materials. By the time suitable electrical welding equipment for welding aluminium became generally available, the purity of commercial argon had been raised to nominally 99·8 per cent., and, in general, experience has shown this to be completely reliable.

Due to the rarity of argon in the atmosphere, and the difficulties associated with its extraction, the cost of the gas is very high—so high in fact, that when used for welding purposes, it becomes the most important item from the point of view of costs. It follows, therefore, that if argon could be diluted, even to a small extent, with some other gas, a marked reduction in running costs would be achieved. Since it appears that one or more of the impurities which are present in low-purity commercial argon are detrimental to the welding process, the present investigation has been undertaken with the two main objects of (*a*) determining the influence of the various impurities on such factors as ease of welding and appearance and quality of welds, and (*b*) determining the possibility of diluting argon with some other gas and still retain good welding conditions. Using 99·8 per cent. argon, the effect of adding various impurities likely to occur in commercial argon and their maximum permissible quantities, were determined.

The principal impurities likely to be present are nitrogen, oxygen and water vapour. Tests were carried out, therefore, in which oxygen and then nitrogen were added to the high-purity argon. Since, however, the introduction of water vapour was likely to give rise to many experimental difficulties, especially in controlling and measuring the amounts introduced, hydrogen was added in its place. This was considered to be permissible as any water vapour would be broken down in the arc into hydrogen and oxygen; the latter element was considered separately in the investigation.

It is generally recognised that the presence of oil or of other hydro-carbons on the base material has a very deleterious effect on the quality of argon-arc welds. To apply known quantities of such substances to an aluminium work-piece is not an easy matter, although it is comparatively simple to introduce gaseous hydro-carbons into the argon. For this reason, a few such tests were carried out, since it was hoped that they would indicate the extent to which substances of this kind could be tolerated in actual practice. Commercial propane was used, which, being a mixture of various paraffin gases, was assumed to be chemically similar to mineral oil.

PREVIOUS WORK

Although most workers recommend that gas of high-purity should be used in the argon-arc process, only Doré, Percival and Sillifant[1] appear to have done any systematic work on the effect of argon-purity on the quality of welds. These workers carried out welding tests on magnesium-rich alloys, using several grades of commercial argon, varying in purity from 95·4 to 98·8 per cent. The main findings were as follows: (1) When using low-purity argon (95·4 and 96·5 per cent.), it was found necessary to increase the flow of gas above the normal value to eliminate a white deposit which formed over the weld area; (2) for fillet welds no difference whatever was observed in the quality of the welds; and (3) no appreciable difference was noted when the gas was oxygen-free, and argon seriously contaminated with nitrogen did not appear to influence the welding operation.

In the U.S.A., where helium as well as argon is employed extensively, it was soon found that the helium should also be of high purity. According to the American Bureau of Mines,[2] helium of 99·8 per cent. purity is markedly superior to that of 98·2 per cent. as regards the quality of welds in aluminium, and the result of extensive tests show that the gas should be as free from hydrogen, nitrogen, water and hydrocarbons as possible.

Lancaster[3] attempted to dilute the argon used for the welding of stainless steel with both nitrogen and hydrogen, but these gases were found to have very objectionable effects on the characteristics of the arc and on the quality of the resulting weld beads.

EXPERIMENTAL WORK

Welding Equipment

The welding equipment employed in the investigation was a composite argon-arc set,† incorporating D.C. suppressors and an H.F. generator.

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* Technical Officer, I.C.I., Metals Division, Birmingham. Formerly an investigator on welding research for the Aluminium Development Association at the University of Birmingham.

† Arc Manufacturing Co. Ltd.; torch by British Oxygen Co. Ltd.

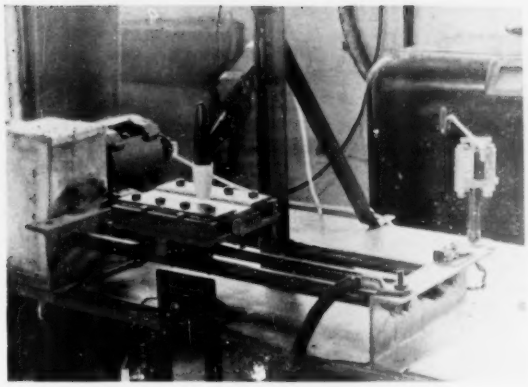

Fig. 1. General view of automatic traverse and welding torch.

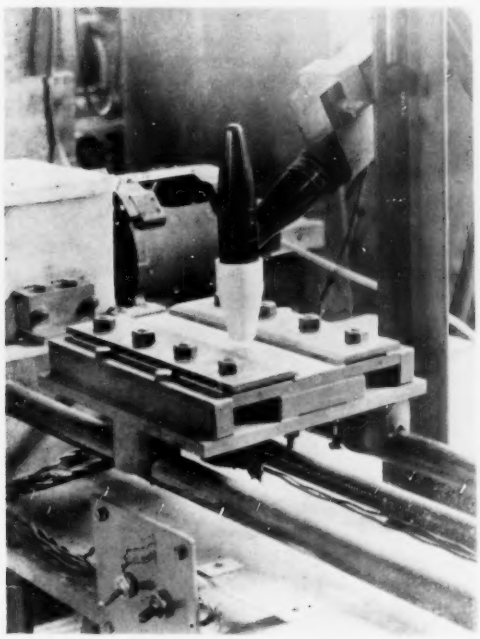

Fig. 2. View of travel-carriage and torch assembly.

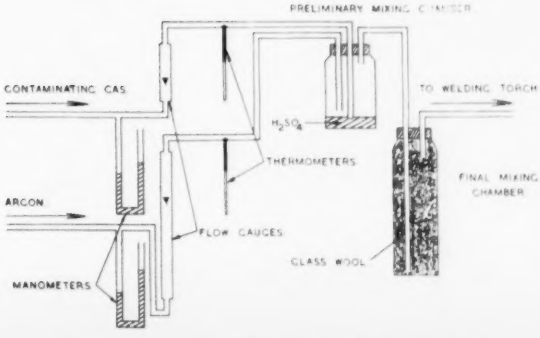

Fig. 3.—Apparatus for mixing other gases with argon.

To obtain constant and reproducible welding conditions the apparatus shown in Figs. 1 and 2 was employed consisting of a device for holding the welding torch and a travel-carriage for moving the work beneath it. The torch was held in a cradle bolted to an angle-iron support, which was slotted to permit adjustment of the arc-length. The nozzle and electrode were always at right angles to the travel-carriage in the longitudinal direction, and adjustments could be made to the cradle to ensure that the torch was upright. The travel-carriage was moved along two guide bars at approximately 6 in./min. by the rotation of a screwed shaft, driven through a gear box by a small electric motor. A small jig for holding the aluminium sheets rested on the carriage. Two supporting blocks and two spacing pieces ensured that the jig was firmly held during each welding test.

In all tests, the torch was fitted with a $\frac{1}{2}$-in. ceramic nozzle and a tungsten electrode of $\frac{1}{8}$ in. diameter projecting $\frac{1}{8}$ in. beyond the nozzle. Depending on the composition of the sheet and the type of test, a current ranging from 75 to 120 amp. was used and arc stabilisation was provided by continuous H.F. spark injection.

Argon of 99·8 per cent. purity was employed throughout the whole of the investigation. Preliminary tests carried out with this gas, in which the principal impurity was nitrogen, indicated that it was completely satisfactory for welding purposes, because all welds were consistently clean and of good appearance. The contaminating gases were commercially pure oxygen, oxygen-free nitrogen, oxygen-free hydrogen and commercial propane.

Gas Apparatus

A diagrammatic view of the apparatus for introducing the impurities is shown in Fig. 3. The argon and the contaminant were led via float-type flowmeters to the preliminary mixing chamber containing a small quantity of concentrated sulphuric acid.

The tube for carrying the contaminant into the first chamber was arranged so that it projected slightly below the surface of the acid, but the argon inlet was slightly above the acid level. By this method an attempt was made to dry the contaminating gas but not the argon, since at the low pressures of working and at the particularly high rates of flow needed for welding, little or no dehydration of the argon could be accomplished. Purification at high pressures was a possibility, but it was felt that the investigation did not warrant the construction of the necessarily involved apparatus, since the argon was known to be sufficiently pure for welding purposes.

After mixing in the first chamber, the gases were led into a second vessel, which contained tightly packed glass wool, and then to the welding torch. The results of numerous preliminary tests showed that this two-stage method of mixing was satisfactory.

The two flowmeters were calibrated from 1 to 10 litres of argon per minute and from 0·02 to 0·2 litres of oxygen per minute respectively. Manometers and thermometers were fitted in the gas lines, so that the instrument-readings could be corrected for temperature and pressure.

When an oxygen flowmeter was used for the other gases the calibrations had to be corrected in order to allow for the differences in the densities of the gases. In all cases, however, gas flows were calculated at a pressure of 760 mm. and at a temperature of 15 deg. C. irrespective of the ambient conditions, and, throughout, the quoted compositions of contaminated gas are by volume and in respect to argon of 99·8 per cent. purity.

In each test the argon flow was adjusted before the introduction of the contaminant, and a period of at least 30 seconds was allowed for the system to become stable before welding commenced. During the tests small fluctuations in the flow

of the two gases occurred and it was necessary to make minor adjustments to the valves. The flows of the gases could then be maintained within very narrow limits. On the completion of each test, the flow of the contaminating gas was stopped, and the argon flow maintained for a further 30 secs. This treatment cleared the whole system of contaminated gas and permitted the electrode to cool in moderately pure argon.

Materials

Fourteen s.w.g. super-pure aluminium and an aluminium-magnesium alloy sheet of commercial purity containing approximately 5 per cent. magnesium were used in the investigation in the fully annealed condition.

A cleaning treatment was given to all the sheets immediately prior to the tests, consisting of thorough degreasing followed by scratch-brushing with a rotating wire brush.

Test Procedure

In the initial stages of the work, a simple weld-bead test was employed, in which sheet was moved beneath the welding torch at an arc-length of $\frac{1}{8}$ in. A current of 90 amp. was used in the tests on super-pure aluminium and 75 amp. with the aluminium-magnesium alloy. These currents were just sufficient to give extremely small underbeads when high-purity argon was used.

Subsequently both filled and unfilled butt welds were made in super-pure aluminium. A current of 115 amp. and an arc-length of $\frac{1}{8}$ in. were used for making all the unfilled welds, but both of these values had to be increased for the filled welds, i.e. 120 amp and arc-length of $\frac{1}{4}$ in. to facilitate the feeding in of the filler rod. Filler rods, cut from the parent sheet, were fed into the weld pool by hand.

Due to the cost of argon the amount used in welding is extremely important. In most of the tests a gas flow of 4 litres per minute was used in addition to the normal flow of 7 litres per minute. As corrections for temperature and pressure were often necessary, variations up to 2 to 3 per cent. occurred at both the gas flow levels used in the tests.

EXPERIMENTAL RESULTS

Contamination with Oxygen

Weld-bead Tests

The introduction of very small amounts of oxygen (0·3-0·5 per cent.) immediately affected the appearance of the weld runs and the arc characteristics. First, the cleaning action of the arc was reduced appreciably, and this was shown by a reduction in the width of the arc-sputtered zone, which became ragged at the edges and along its length and was very irregular in the severity of the surface attack. Secondly, the weld beads showed some tendency to wander and did not generally present a very satisfactory surface appearance. Several other effects were observed, e.g. the heat of the arc appeared to become more intense, shown by increased weld penetration, and increased electrode wear was noticeable. A fine deposit of yellow tungstic oxide occurred on the surfaces of the test-plates, and after the completion of each welding run, the electrode was discoloured similar to an electrode inadequately protected during cooling.

As the oxygen content was increased, the above effects became more apparent, and the quality of the welds deteriorated rapidly to an extent depending on the gas flow and the composition of the basis metal, being more severe at the lower gas flow and with the aluminium-magnesium alloy. With more than 1 per cent. oxygen the beads were covered with a thick layer of oxides, and the arc became very erratic.

Welding Tests

At a gas flow of 7 litres per minute satisfactory unfilled welds could be made with argon containing up to about 0·6 per cent. oxygen, although the surface appearance was poor. With more than 0·6 per cent. oxygen the oxide films became pronounced and appeared to interfere to some extent with the proper consolidation of the weld beads, although further examination showed these welds to be reasonably sound.

The introduction of very small amounts of oxygen caused a marked deterioration in the appearance of the filled welds, e.g. compare the weld made using high-purity argon at a flow of 7 litres per minute shown in Fig. 4, and one made at the same gas flow but with argon containing 0·3 per cent. oxygen shown in Fig. 5. The first weld is clean and has a well defined, arc-sputtered zone, but the second exhibits a very narrow, irregularly cleaned zone and oxides occur on the surface of the weld bead. These oxides, however, did not interfere in any way with the welding operation.

As the oxygen content was increased the appearance of the welds continued to deteriorate and welding became difficult due to patches of tungsten and aluminium oxides on the surface of the weld pool. In general, welding was equally easy with an argon-0·7 per cent. oxygen mixture at 7 litres per minute and an argon-0·5 per cent. oxygen mixture at 4 litres per minute. With higher percentages of oxygen, welding became increasingly difficult, and the resulting welds were far from satisfactory. Figs. 6 and 7 show two welds made at 7 litres per minute with argon containing 0·6 and 1·4 per cent. oxygen respectively. Marked oxide-deposits occur on the surface of the specimen in Fig. 6, and it will be seen that these have interfered with the proper flow of the molten weld pool. This effect is more pronounced in the weld bead shown in Fig. 7, which shows a marked tendency to wander and is totally covered with oxide.

Contamination with Nitrogen

Weld-bead Tests

Small amounts of nitrogen appeared to have little effect on the characteristics of the arc or the appearance of the beads. The electrode operated efficiently and did not erode, and, on cooling in the gas shroud, exhibited the clean bright surface characteristic of operation in high-purity argon.

With increase in the nitrogen content, the arc became more difficult to strike, and the width of the arc-sputtered zone gradually decreased, becoming less severely attacked and taking on a slight brown colouration. The width and penetration of the weld beads increased, indicating increased heat in the arc.

The brown deposits on the surface of the weld bead depended on the nitrogen content of the gas and the composition of the workpiece. The nitrogen contents to produce these deposits were higher for super-pure aluminium than for the aluminium-magnesium alloy and also higher in general the greater the flow of gas. For example, at a flow of 7 litres per minute, the deposit first occurred on the super-pure aluminium at a nitrogen content of 1·5 per cent., whereas its first appearance on the alloy was at 0·9 per cent. At 4 litres per minute, however, the figures were 2·6 and 0·5 per cent. respectively. When the nitrogen was increased above these values, the deposits assumed a more massive form, and when the nitrogen content reached of the order of 4 per cent., the whole of the fused area was completely enveloped.

Welding Tests

Satisfactory unfilled butt welds could be made at a gas flow of 7 litres per minute with nitrogen contents as high as 4 per cent. In all cases, the presence of nitrogen in no way interfered with the proper consolidation of the weld

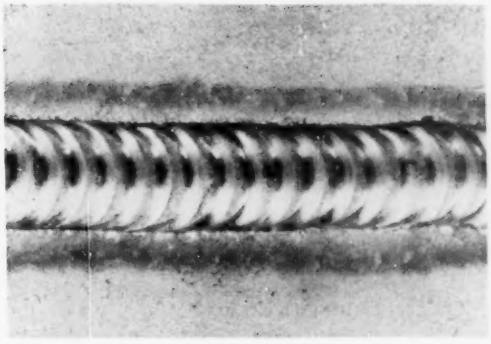

Fig. 4. Filled butt weld in super-pure aluminium. Gas flow: 7 litres/min. Pure argon. × 2.

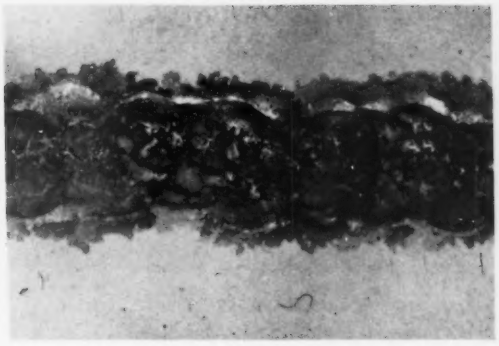

Fig. 7. Filled butt weld in super-pure aluminium. Gas flow: 7 litres/min. Oxygen content: 1·4 per cent. × 2.

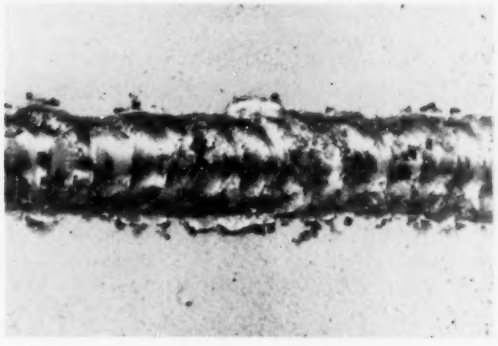

Fig. 5. Filled butt weld in super-pure aluminium. Gas flow: 7 litres/min. Oxygen content: 0·3 per cent. × 2.

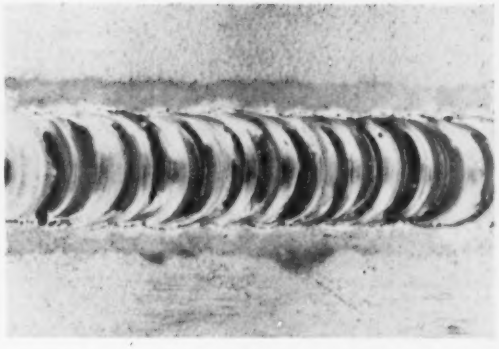

Fig. 8. Filled butt weld in super-pure aluminium. Gas flow: 7 litres/min. Nitrogen content: 0·8 per cent. × 2.

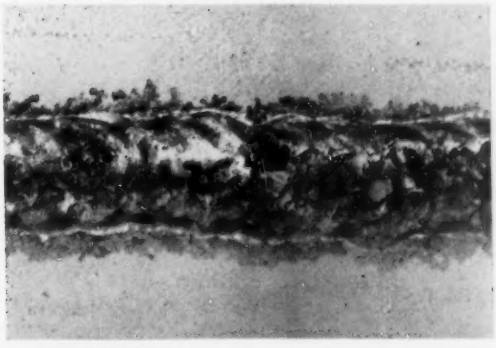

Fig. 6. Filled butt weld in super-pure aluminium. Gas flow: 7 litres/min. Oxygen content: 0·6 per cent. × 2.

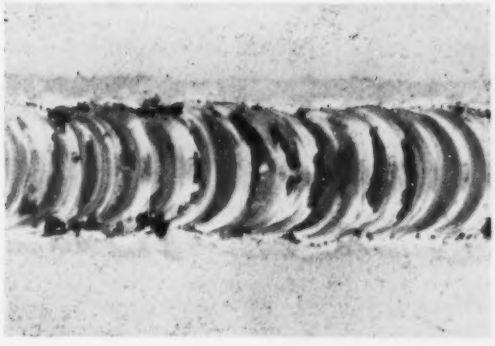

Fig. 9. Filled butt weld in super-pure aluminium. Gas flow: 7 litres/min. Nitrogen content: 1·5 per cent. × 2.

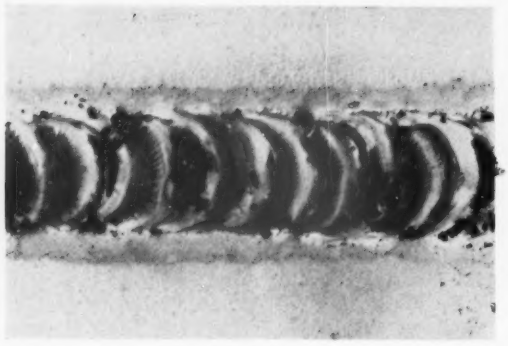

Fig. 10. Filled butt weld in super-pure aluminium. Gas flow: 7 litres/min. Nitrogen content: 4·0 per cent. ×2.

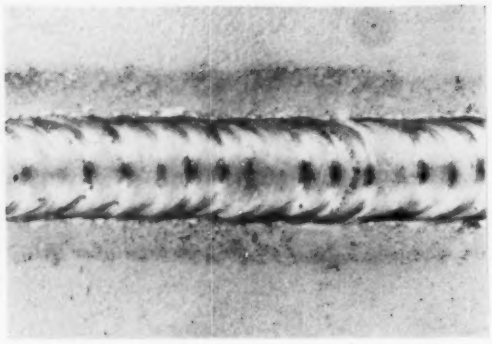

Fig. 11. Filled butt weld in super-pure aluminium. Gas flow: 7 litres/min. Hydrogen content: 1·1 per cent. ×2.

beads, even when sufficient was present to produce marked amounts of surface deposit.

With filled welds there was little difference between an argon-0·3 per cent. nitrogen mixture and high-purity argon, except that with the former the weld area was covered with a slightly greyish film. This film became more pronounced as the nitrogen content was increased and gradually assumed the brown colouration of the deposit observed in the weld-bead tests. As might be expected, these films were always more severe on the welds made with a gas flow of 4 litres per minute, although in general they rarely interfered with the satisfactory flow of the weld pool and the addition of the filler metal, except when the nitrogen exceeded 3 per cent. Figs. 8, 9 and 10 show three filled welds made at a gas flow of 7 litres per minute with 0·8, 1·5 and 4·0 per cent. nitrogen respectively. These illustrate very clearly the extent of the deterioration in surface appearance as the nitrogen was increased and also indicate the reduced cleaning action of the arc.

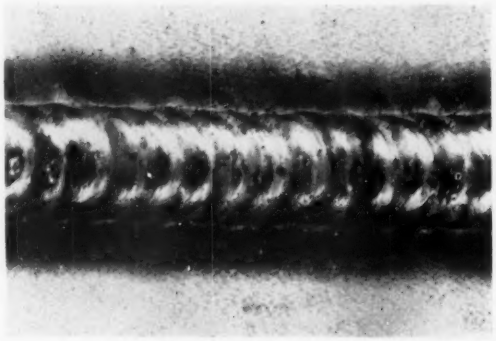

Fig. 12. Filled butt weld in super-pure aluminium. Gas flow: 7 litres/min. Hydrogen content: 4·4 per cent. ×2.

Contamination with Hydrogen

Weld-bead Tests

The gas flow used in all tests with hydrogen was 7 litres per minute and marked effects were noticeable with a 1 per cent. addition. As in the previous tests with oxygen and nitrogen, the contaminant reduced the cleaning action of the arc and also increased its heating effect. Although hydrogen had no adverse effects on the tungsten electrode, the weld beads appeared swollen and exhibited surface porosity, which was always more pronounced with super-pure aluminium.

All the above effects became more pronounced with increase in the hydrogen content, and at 3 per cent. in the tests on super-pure aluminium and at about 2 per cent. in the tests on the alloy, the sheet adjacent to the fused zone became discoloured and a dark deposit occurred along the fusion lines. Greater amounts of hydrogen caused general dirt films, which completely enveloped the fused area when the content reached of the order of 4 per cent.

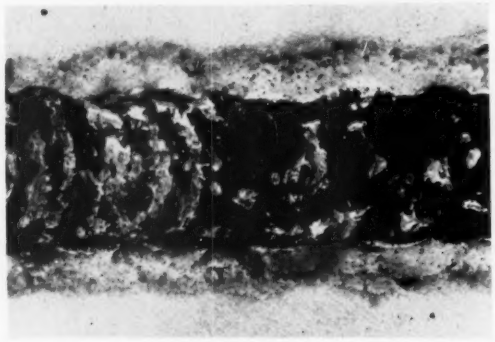

Fig. 13. Filled butt weld in super-pure aluminium. Gas flow: 7 litres/min. Hydrogen content: 5·4 per cent. ×2.

Welding Tests

The presence of hydrogen did not prevent the proper consolidation of the unfiilled welds even when sufficient was present to cause severe deposits of dirt and extremely marked porosity. This was also true of the filled welds which could be made as easily when 4 per cent. hydrogen was present as with high-purity argon. With increasing amounts such heavy deposits occurred on the weld pool that it became difficult to feed in the filler rod.

Filled butt welds using contaminated argon are illustrated in Figs. 11, 12 and 13, the hydrogen contents being 1·1, 4·4 and 5·4 per cent. respectively. These photographs provide a good indication of the very harmful effects of hydrogen on the appearance of weld beads and also to a smaller extent its effect on the heat liberated in the arc.

Contamination with Propane

Only two tests were carried out with argon contaminated with propane. The first was a weld-bead test and the second an unfilled butt weld—each on super-pure aluminium using

a gas flow of 7 litres per minute. In both tests the smallest measurable addition was made (0·2 per cent.) when calculated as pure propane. The beads obtained with this mixture were completely covered with a black deposit. In addition, the weld beads presented a swollen appearance similar to those made with argon-hydrogen mixture, and heavy penetration indicated that the propane had increased the heating effect of the arc.

Metallographic Examination

Metallographic examination was carried out on many of the welds made at a gas flow of 7 litres per minute. When high-purity argon was employed, the welds were, in general, free from both dirt and porosity. When such defects occurred, however, they were always small and of no real significance.

The welds made with argon contaminated with oxygen showed varying amounts of oxide-inclusions, especially those to which filler metal was added. These inclusions were never of a serious nature, however, except in welds where the oxygen exceeded about 1 per cent.

Generally, the welds made with argon-nitrogen mixture were remarkably sound, and, although small amounts of dirt did occur in the weld beads, these inclusions could not be regarded as being of any consequence. Inclusions of aluminium nitride occurred in the welds when the argon shield contained 4 per cent. nitrogen, and on microscopic examination these inclusions appeared as finely divided needles.

The welds made with an argon-hydrogen mixture showed marked internal porosity, which increased in severity with increase in the hydrogen content. The one unfilled weld made using argon contaminated with propane exhibited similar effects, and in addition the weld metal contained a large amount of dirt finely dispersed in the form of spherular particles.

DISCUSSION

Effect of Impurities on the Quality of Welds

The results of the investigation may be summarised as in the Table, which, apart from indicating the principal effects of the impurities, also gives recommendations as to the maximum amounts which can be tolerated for reasonably satisfactory welding. These results confirm those of general experience, namely, that for the satisfactory argon-arc welding of aluminium and its alloys, argon of the highest possible purity should be employed. It has been shown, however, that small amounts of impurities can be tolerated without great detriment to the welds, the amount depending upon the impurity, the argon flow, the type of weld and, to some extent, the material.

Oxygen is a particularly harmful impurity, even when present in very small amounts, since it causes the electrode to oxidise and erode. From the welding point of view, however, oxygen can be tolerated in small quantities, but with gas flow of about 7 litres per minute, the content should never exceed about 0·3 per cent. if welds of a pleasing appearance are to be obtained. If the material being welded contains any readily oxidisable elements, such as magnesium or a low gas flow is used, the oxygen content should be much lower than 0·3 per cent.

Nitrogen is a much less harmful impurity, since it causes no attack of the electrode and appreciable amounts may be present before the weld appearance deteriorates. Higher nitrogen contents can be tolerated for unfilled welds than for filled welds, but as with oxygen the amount depends on the gas flow and probably on the composition of the basis metal. In general, satisfactory welding conditions should be obtained if the nitrogen does not exceed about 1 per cent.

If the combined results obtained in the tests with oxygen and hydrogen provide an indication of the possible effects of water vapour, it is immediately clear that this impurity must be avoided at all costs. Hydrogen causes marked porosity when present in only small amounts. A little water is present in the argon supplied for welding purposes, but at the pressures at which it is stored in cylinders, this water must exist mainly as liquid; not until the pressure is reduced appreciably can it vaporise. It is a well-known fact that the last quantities of argon withdrawn from cylinders may result in dirty and porous welds.

The tests with propane indicate the very harmful effects hydrocarbons can have on the quality of argon-arc welds, since they result in porosity and inclusions. It is clearly important, therefore, that components should be thoroughly degreased prior to argon-arc welding.

Effect of Impurities on Arc Characteristics

A number of observations of a more fundamental nature were made during the course of the investigation. For example, the presence of oxygen, nitrogen and hydrogen appeared to cause an increase in the heating effect of the arc. This phenomenon is easily accounted for by the fact that all these gases are diatomic (*cf.* argon, which is monatomic) and are disassociated at the high temperatures of the arc. The resulting atoms diffuse to the surfaces of the electrode and the workpiece, where they recombine liberating

Table.—Gaseous Additions to Argon and their Effect on Weld Quality and Arc Characteristics

Added Gases	Principal Effects					Permissible Content (per cent.)
	Weld Quality		Arc Characteristics			
	Surface Appearance	Soundness	Electrode	Cleaning Action	Heating Effect	
Oxygen	Very poor	Harmful	Extremely detrimental	Very harmful	Increased	0·3
Nitrogen	Poor	Harmful	No apparent effect	Fairly harmful	Increased	1
Hydrogen	Poor	Extremely harmful	No apparent effect	Fairly harmful	Increased	Minimum attainable
Water (by inference)	Very poor	Extremely harmful	Extremely detrimental	Very harmful	Increased	Minimum attainable
Propane and other hydrocarbons	Very poor	Extremely harmful	No apparent effect	Harmful (by inference)	Increased	Minimum attainable

the energy of association. In this respect it is noteworthy that hydrogen was found to increase the heating effect of the arc more than either of the other gases. This is probably due to its higher degree of disassociation at arc temperatures and to its higher diffusion coefficient.

The association of hydrogen atoms at the surface of the aluminium is not complete, however, since all the welds showed internal porosity. Now only hydrogen in the atomic form could diffuse into the molten metal to cause such porosity. Similarly the porosity which occurred in the weld made using argon contaminated with propane would appear to be caused by the hydrogen formed in the decomposition of the hydrocarbons at the arc temperatures. This hydrogen would be in the atomic form and therefore capable of diffusion. In addition some would associate at the surface of the workpiece resulting in an additional heating effect.

One very interesting finding was that the presence of oxygen, nitrogen and hydrogen reduce the cleaning action of the arc both in the area affected on the workpiece and in the severity of the attack. The most acceptable explanation for the narrowing of the arc-sputtered zone would appear to be that these gases alter the electron-emission characteristics of the basis metal in some way; they may, for example, increase the work function. With regard to the degree of surface attack, the reductions would be expected perhaps, since if the cleaning action is the result of positive-ion bombardment, it must be dependent on the mass of the impacting positive ions. The atomic weight of argon is greatly in excess of those of oxygen, nitrogen and hydrogen. When welding is carried out with pure argon, all the ionisation in the arc is supplied by the argon, and hence in this case argon ions are responsible for the bombarding effect. Since the ionisation potentials of the above impurities are lower than that of argon, when these impurities are present all or the greater part of ionisation will be supplied by them. The effects of the different impurities are not of the right order of magnitude, however, when their atomic weights are taken into account, for on this basis hydrogen ought to be the most effective. This is not the case since oxygen was found to have the greatest influence. No explanation can be advanced for this irregularity.

Possibility of Diluting the Argon

The present investigation, although of a somewhat limited nature, has shown conclusively that the argon cannot be diluted with nitrogen or hydrogen without introducing a number of harmful effects. In addition, the results of the work suggest that it is most unlikely that any gas can be found, other than another inert gas, which could be used for dilution. Chlorine and fluorine are the only other non-inert elements which are gaseous at room temperature, and these gases would undoubtedly attack both the electrode and the material being welded, apart from introducing many technical difficulties. There are numerous gaseous compounds, however, but, in general, they contain one or a combination of the following elements: hydrogen, oxygen, nitrogen, carbon, sulphur and phosphorus. At the high temperatures of the arc, these compounds would be dissociated liberating elements which clearly would be detrimental to the welding process.

CONCLUSIONS

1. For the satisfactory argon-arc welding of aluminium and its alloys, argon of the highest possible purity should be employed. Small amounts of impurities can be tolerated, however, without great detriment to the welds, the amount depending on (*a*) the impurity, (*b*) the argon flow, (*c*) the material, and (*d*) the type of weld.

2. Oxygen is a particularly harmful impurity, even when present in very small amounts, since it causes oxidation and erosion of the tungsten electrode and results in welds which have a very poor appearance. It is recommended that the oxygen content should never be permitted to exceed about 0·3 per cent.

3. Nitrogen is a much less harmful impurity, since it causes no electrode erosion and larger amounts can be present before the appearance of the welds deteriorates. The nitrogen content should never exceed about 1 per cent.

4. Hydrogen causes severe porosity, and since oxygen also has very undesirable effects, it would appear that water vapour is likely to be an extremely harmful impurity.

5. Hydrocarbons have most objectionable effects, and for this reason it is recommended that components should be thoroughly degreased prior to welding.

6. It is most unlikely that any gas can be found, other than another inert gas, which could be used to dilute the argon used in the argon-arc welding process.

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